Editorial Manager(tm) for International Congress Series
Manuscript Draft

Manuscript Number:

Title: An electro-magnetically tracked laparoscopic ultrasound for multi-modality minimally invasive surgery

Article Type: Full Length Article (FLA)

Section/Category:

Keywords: laparoscopic ultrasound; electro-magnetic tracking; radio-frequency ablation; ultrasound/CT registration; image-guided therapy

Corresponding Author: Dr Jochen Kruecker, PhD

Corresponding Author's Institution: Philips Research USA

First Author: Jochen Kruecker, PhD

Order of Authors: Jochen Kruecker, PhD; Anand Viswanathan, MS; Joern Borgert, Dr.; Neil Glossop, PhD; Yibin Yang, PhD; Bradford Wood, MD

Manuscript Region of Origin:

Abstract: An experimental workstation and surgical tools are presented utilizing electro-magnetic tracking to register real-time laparoscopic ultrasound (LUS) images with static pre-acquired CT volumes. The registration and image fusion were used to guide tracked needles to target locations in an abdominal phantom. A custom-made sleeve equipped with magnetic sensor coils and attached to the steerable tip of a commercial LUS probe allowed precise localization of the imaging array without line-of-sight restrictions. For registration with CT image space, landmarks in physical space were identified using three different methods: (1) by pointing with a separate, electro-magnetically tracked pointer, (2) by pointing with the tip of the laparoscope, or (3) by imaging and subsequent manual identification of the landmark with LUS. The root-mean square (RMS) registration error using the three methods was 1.5 mm, 1.4 mm, and 1.1 mm, respectively. Overlays of real-time LUS with pre-acquired CT demonstrated the registration quality. Based on these registrations, tracked needles were guided into user-defined target locations. The RMS placement accuracy was 1.8 mm, 1.3 mm, and 1.9 mm, respectively. Accuracy is sufficient for planned clinical trials.

An electro-magnetically tracked laparoscopic ultrasound for multi-modality minimally invasive surgery

Jochen Krücker[a,*], Anand Viswanathan[b], Jörn Borgert[c], Neil Glossop[d], Yibin Yang[a], Bradford J. Wood[b]

[a]*Philips Research USA, Briarcliff Manor, NY, USA*
[b]*Diagnostic Radiology Department, National Institutes of Health, Bethesda, MD, USA*
[c]*Philips Research Laboratories, Sector Technical Systems, Hamburg, Germany*
[d]*Traxtal Inc ,Bellaire, TX, USA*

Abstract. An experimental workstation and surgical tools are presented utilizing electro-magnetic tracking to register real-time laparoscopic ultrasound (LUS) images with static, pre-acquired CT volumes. The registration and image fusion were used to guide tracked needles to target locations in an abdominal phantom. A custom-made sleeve equipped with magnetic sensor coils and attached to the steerable tip of a commercial LUS probe allowed precise localization of the imaging array without line-of-sight restrictions. For registration with CT image space, landmarks in physical space were identified using three different methods: (1) by pointing with a separate, electro-magnetically tracked pointer, (2) by pointing with the tip of the laparoscope, or (3) by imaging and subsequent manual identification of the landmark with LUS. The root-mean square (RMS) registration error using the three methods was 1.5 mm, 1.4 mm, and 1.1 mm, respectively. Overlays of real-time LUS with pre-acquired CT demonstrated the registration quality. Based on these registrations, tracked needles were guided into user-defined target locations. The RMS placement accuracy was 1.8 mm, 1.3 mm, and 1.9 mm, respectively. Accuracy is sufficient for planned clinical trials.

Keywords: Laparoscopic ultrasound; Electro-magnetic tracking; Radio-frequency ablation; Image fusion; Ultrasound/CT registration; Image -guided therapy

---

1. Introduction

Minimally invasive surgery and interventional procedures, combined with image-guidance technologies, have shown increasingly promising results in recent years compared with traditional open surgery. Advantages of less invasive procedures include shorter hospital stays or use in an outpatient setting, reduced cost, less blood loss, faster recovery from the procedure, and reduced use of pain medication.

* Corresponding author. *E-mail address*: Jochen.Kruecker@philips.com

In addition, some interventional and minimally invasive procedures can be performed in patients not considered candidates for surgery due to age, extent of disease, or other factors. Radiofrequency ablation (RFA) is an interventional procedure that has become a standard treatment option for certain unresectable primary and secondary malignant hepatic tumors, and is being studied for multiple oncology applications like lung and kidney tumors and painful bone metastases [1]. RFA is generally performed under ultrasound (US), computed tomography (CT), or magnetic resonance imaging (MRI) guidance. In most cases, liver RFA can be performed percutaneously or laparoscopically, and open surgical exposure of the liver is only required in some cases [2].

The least invasive approach, percutaneous RFA, relies on adequate visualization of the tumor using percutaneous imaging. Percutaneous ultrasound generally can be used to provide image guidance but the image quality may suffer when trying to image through a thick layer of abdominal fat, or if the tumor location is too far below the skin surface. In such cases, laparoscopic ultrasound (LUS) can provide superior image quality by placing the imaging probe directly on the liver surface. The most common advantage of LUS over the percutaneous approach is that RFA may be safely performed adjacent to bowel, nerve, ureter, or other sensitive collateral structure, following surgical dissection or insulating protection from carbon dioxide gas or a gauze. One disadvantage of laparoscopic ultrasound is the difficulty in relating the ultrasonic image plane to the patient anatomy, because standard orientations used in trans-abdominal ultrasound cannot be used laparoscopically [3]. Thus, interpreting LUS images requires significant expertise. Electromagnetic tracking of the laparoscope and registration of the LUS with a pre-acquired volumetric image, such as CT or MRI, offers potential benefits in the image interpretation [4].

A second benefit offered by tracked LUS is that it allows registration using internal landmarks for tracked needle-based procedures. Electro-magnetically tracked needles can be used for biopsies and ablations, and may complement or replace real-time image guidance during these procedures. Given the strong deformation of the abdominal region due to the CO_2 insufflation during laparoscopic procedures, external landmarks would be insufficient to provide registration with a pre-acquired data set. With electro-magnetic tracking, the position and orientation of a needle can be directly related to a pre-acquired volumetric image, thus guiding the needle on a path toward a pre-selected target without real-time imaging, or by using additional visual targeting feedback superimposed on a real-time image. Lesions such as neuroendocrine pancreatic tumors and small hereditary kidney tumors may be difficult to localize in relation to pre-operative imaging, partly due to multiplicity of lesions. Tracked LUS could localize and identify which lesions are targeted, when the target may be only identified with special contrast agents and is one of many candidate lesions.

We present a prototype workstation and device enabling registrations and needle targeting using an electro-magnetically tracked laparoscope. The accuracy of different registration techniques and of subsequent needle targeting is evaluated in phantom experiments.

2. Materials and Methods

A laparoscopic ultrasound transducer with a 9 MHz linear array (Philips Medical Systems, Andover, MA) was equipped with a custom-fitted electro-magnetic sensor

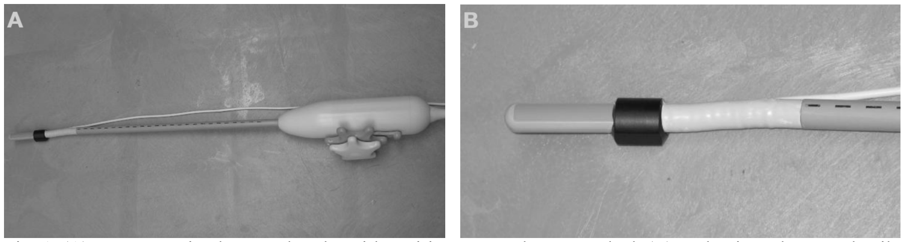


Fig. 1. (A) Laparoscopic ultrasound probe with position sensor sleeve attached. (B) Probe tip and sensor detail.

(Traxtal Inc., Bellaire, Texas). **Fig. 1** shows the sensor sleeve attached to the steerable tip of the probe, immediately adjacent to the ultrasound array.

The sensor sleeve is compatible with the Aurora magnetic tracking system (Northern Digital Inc., Waterloo, CA) and encodes 6 degrees of freedom (DOF). Two calibration procedures were performed to relate tracking coordinates recorded with the tracking system to physical and image coordinates:

(1) The most distal part of the laparoscopic probe was identified as "probe tip". The position of the probe tip relative to the coordinate system of the sensor sleeve was determined by positioning the probe tip onto the tip of a needle and exercising 6 DOF motion around the needle tip while recording magnetic tracking data from the sleeve. Singular value decomposition of the recorded transformation matrices allows least-squares estimation of the offset from sensor coordinates to probe tip. This calibration allows usage of the laparoscopic tip as an electro-magnetically tracked pointer device. The accuracy of this calibration was established by subsequent tracking of the laparoscope relative to a calibrated tracked pointer positioned on the probe tip, and was estimated to be better than 1 mm.

(2) The second calibration established the relationship between the sensor coordinates and the image coordinates of the ultrasound image generated by the laparoscope. This calibration was performed for a fixed imaging depth of 7.9 cm, which was used for all subsequent experiments. The calibration involved obtaining ultrasound images with the tracked laparoscope in a custom-made cross wire phantom and manually identifying the crossed wires in the images, which served as a point target. Singular value decomposition was used to determine the relationship between ultrasound image coordinates and tracker space coordinates based on the location of the point targets and corresponding tracker data. The accuracy of this calibration was better than 0.7 mm RMS throughout the field of view.

All validation experiments were performed in an abdominal multi-modality imaging phantom (Computerized Imaging Reference Systems, Norfolk, VA). The phantom was customized to include approximately 10 hypo-echoic spherical lesions with diameters of 10 to 20mm in the liver part of the phantom. Six of these lesions were located within the imaging depth of the LUS. Five of the lesions were used as landmarks for registration purposes, the sixth lesion served as a target for evaluation of tracked needle placements. Radio-opaque fiducial markers (Beekley Corp., Bristol, CT) were attached to the outside of the phantom to serve as reference points for registrations with pointer-like devices.

CT scans of the phantom were obtained using a Philips MX8000 scanner. A slice thickness of 2 mm with 50% overlap and a 400 mm field of view were chosen for all scans. The first scan served as a reference and was used to register ultrasound image space and tracking space with CT image space. Following each needle placement, one additional CT scan was obtained to verify the needle position and serve as a gold standard in determining the accuracy of needle placement.

Custom software was developed to perform the calibrations and registrations, and to provide navigational feedback for advancing a tracked needle into a pre-selected target position inside the phantom. A total of 15 registrations were performed, 10 using the external fiducials and 5 using the internal lesions. Half of the registrations with external fiducials were obtained by touching the fiducials with a commercial, calibrated tracked pointer; the other half were obtained by using the laparoscope tip instead of the pointer. Registrations using the internal landmarks required imaging the central cross section of each landmark with laparoscopic ultrasound. Video frame grabbing was used to display the real-time ultrasound image on a workstation, where the center of each landmark was identified manually.

Once a registration transformation was computed, the real-time ultrasonic image could be fused and visualized with the pre-acquired CT scan. In addition, the registrations could be used to visualize the positions of other tracked interventional devices, such as needles and pointers, relative to the CT image. This was used to guide a 19 gauge tracked stylet to the user-defined target location identified in the CT scan. A special targeting display facilitated the procedure by providing visual feedback regarding the current needle orientation and distance relative to the target.

3. Experiments and Results

The registrations and needle placements were performed with the phantom positioned on an acrylic support structure, approximately 200 mm above the CT table and 900 mm away from the CT gantry. Keeping this distance from table and gantry ensured that the accuracy of the magnetic tracking system was not significantly affected by electro-magnetic interference. Identification of the landmarks and fiducial markers in the CT image took an experienced operator approximately two minutes. Identification of the corresponding physical positions with magnetic tracking took about one minute when using the commercial pointer, and about two minutes when using laparoscopic ultrasound.

The registration results are summarized in Table 1. There was no statistically significant difference between the mean registration errors. The registrations were then used to overlay the laparoscopic ultrasound image onto the pre-acquired CT and to guide a tracked needle to a radio-opaque point target placed in the phantom, and to the center of a lesion identified in the phantom. **Fig. 2** shows examples of the US/CT overlay. Images A and B show two lesions visualized with different opacity of the US image, which was used to demonstrate the accuracy of registration. Image C shows the fused images of a rib structure further away from the lesions used for registration.

Fig. 3 displays a screen shot from the targeting process, after the needle was advanced into the center of the target lesion. The two images to the left show a model of the needle

Table 1
Registration errors (mm) for different registration methods

Registration:	Tracked Pointer	Tracked Laparoscope Tip	LUS Imaging of Landmarks
Mean RMS Error:	1.47	1.35	1.12
Std. Deviation:	0.60	0.50	0.39

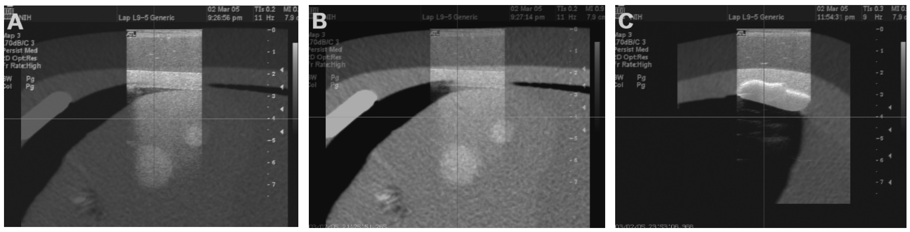


Fig. 2. Overlay of real-time laparoscopic US with pre-acquired CT. The two lesions in the US image in (A) become visible in the same position in the CT image (B) after reducing the opacity of the US overlay. (C) shows good agreement of the rib surface between the US overlay and CT image.

superimposed on orthogonal cross sections through the CT scan at the position of the needle tip. Note that an entry angle not perpendicular to the surface of the phantom was used in order to avoid the rib structure anterior to the lesion. The right image, called the targeting display, shows a cross section through the target lesion and perpendicular to the needle. The small cross in the center indicates the current orientation of the needle and can be used to correct the needle angle during the positioning process.

Table 2 summarizes the results of guided needle placements in the phantom. “Displayed Accuracy” is the needle tip-to-target error indicated by the magnetic tracking system after the operator completed the needle placement. “Confirmed Accuracy” is the tip-to-target error as confirmed by subsequent CT scans and manual identification of true needle tip and target positions. The displayed values are mean and standard deviation based on 5 needle placements each.

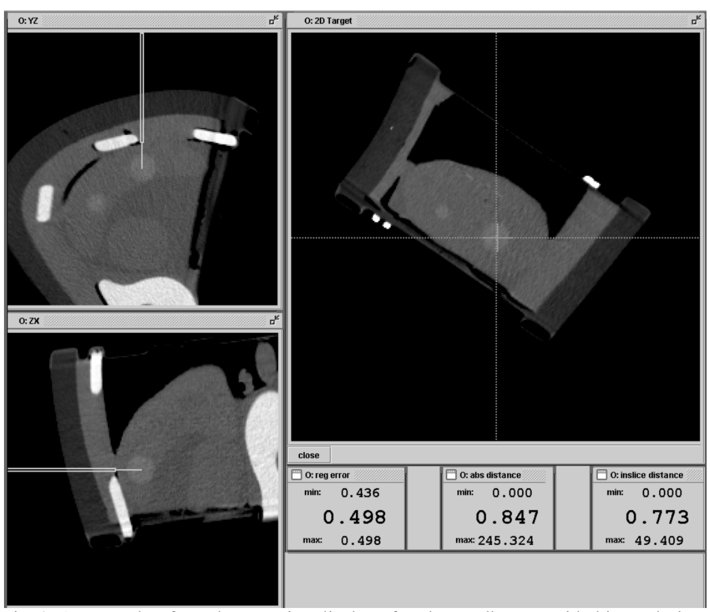


Fig. 3. A screenshot from the targeting display after the needle was guided into a lesion.

Table 2
Needle placement accuracy (mm) based on electro-magnetic tracking guidance alone

Registration:	Tracked Pointer	Tracked Laparoscope Tip	LUS Imaging of Landmarks
Displayed Accuracy:	1.98 ± 1.00	1.36 ± 0.50	1.32 ± 0.68
Confirmed Accuracy:	1.82 ± 1.59	1.27 ± 0.65	1.88 ± 0.81

4. Discussion and Conclusions

An experimental surgical navigation system is presented that integrates laparoscopic real-time ultrasound, pre-acquired CT images, and electro-magnetic tracking. The tracking system is used to register the US with CT, and to guide tracked needles to a target location defined on CT. The primary applications to benefit from this technology are laparoscopic biopsies, radio-frequency ablations, cryo-ablations, and other needle-based procedures, however surgical localization and targeting of hard-to-differentiate lesions in the pancreas, liver, and kidney may potentially expedite and facilitate resection with maximal sparing of normal structures. The fusion of US and CT in a single image may leverage the complementary image information to an extent not achievable when using US and CT independently. This surgical navigation system makes use of the high resolution imaging like CT and MRI that normally are hanging on a light board on the wall far away from the scalpel action in the standard operating theatre. The CT scan allows path planning in 3D, and offers a large field-of-view and high signal-to-noise ratio. Some lesions, however, do not visualize well on CT, even after contrast injection. US alone does not visualize all lesions either but may provide some information in cases where CT fails. Some US contrast agents show promise and the role of US may become more prominent once more advanced contrast agents are approved for clinical use.

While fused US/CT alone may improve path planning and targeting for needle-based procedures, an additional and possibly larger benefit lies in the combination with electro-magnetically tracked needles. As demonstrated in this study, fast and accurate registrations can be obtained using the tracked laparoscope, comparing favorably with previous electro-magnetic tracking studies [5]. This offers the flexibility of using external (skin) and internal (organ surface) superficial landmarks as well as landmarks inside of organs (deeper lesions, vascular bifurcations etc.).

We have also shown that in a stationary phantom these registrations are sufficient to provide very accurate needle guidance based on the tracking information alone. The fast and accurate placement of the needles even by less experienced users suggests that clinical value may be added by the introduction of electro-magnetic tracking.

References

[1] B.J. Wood, J.R. Ramkaransingh, T. Fojo, M. Walther, S.K. Libutti: Percutaneous Tumor Ablation with Radiofrequency. Cancer 2002; 94:443-451

[2] J. R. Leyendecker, G. G. Dodd III, Minimally Invasive Techniques for the Treatment of Liver Tumors, Seminars in Liver Disease, Volume 21, No 2, 283-291, 2001

[3] J. Ellsmere, J. Stoll, W. Wells III et al. A new visualization technique for laparoscopic ultrasonogrpahy, Surgery 136(1): 84-92, 2004

[4] P. Bao, J. Warmath, R. Galloway Jr., A. Herline, Ultrasound-to-computer-tomography registration for image-guided laparoscopic liver surgery, Surgical Endoscopy, 2005

[5] B.J. Wood, H. Zhang, A. Durrani et al., "Navigation with Electromagnetic Tracking for Interventional Radiology Procedures: A Feasibility Study", J. of Vascular and Interventional Radiology, 2005 (in press)

Figure 1A
Click here to download high resolution image

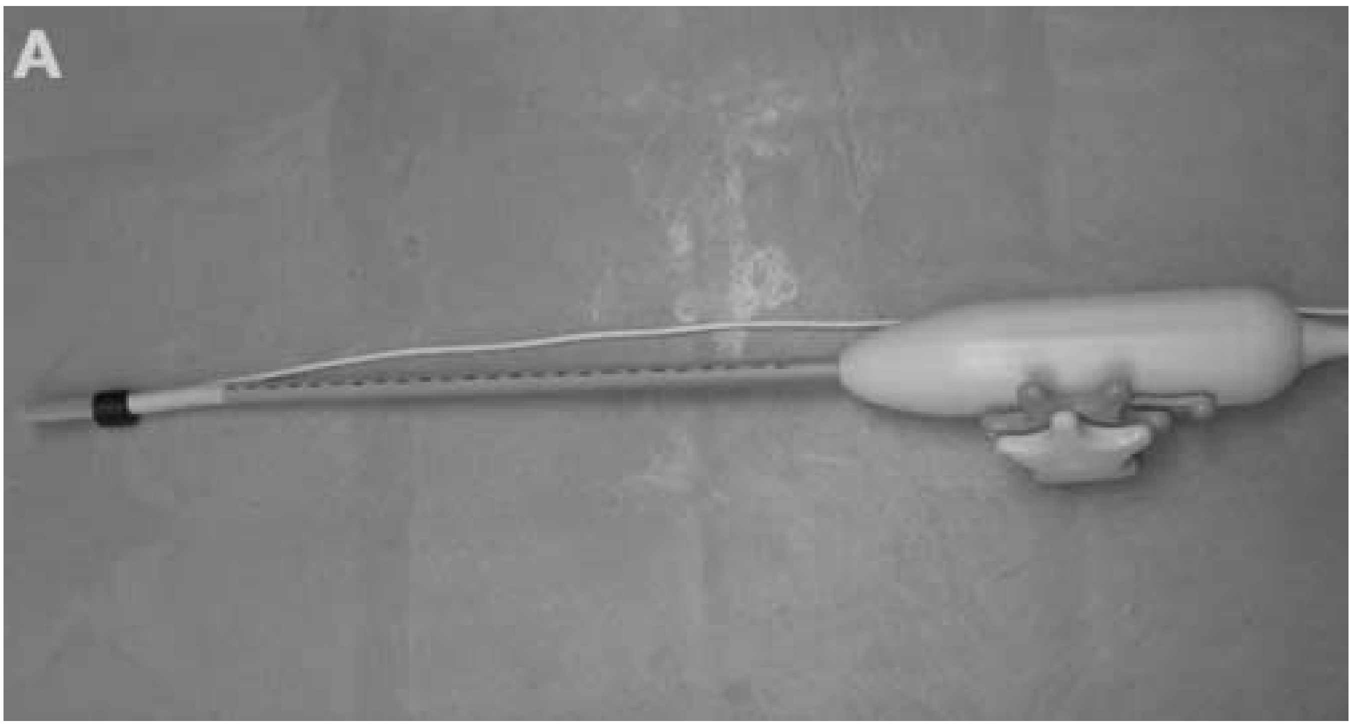


Figure 1B
Click here to download high resolution image

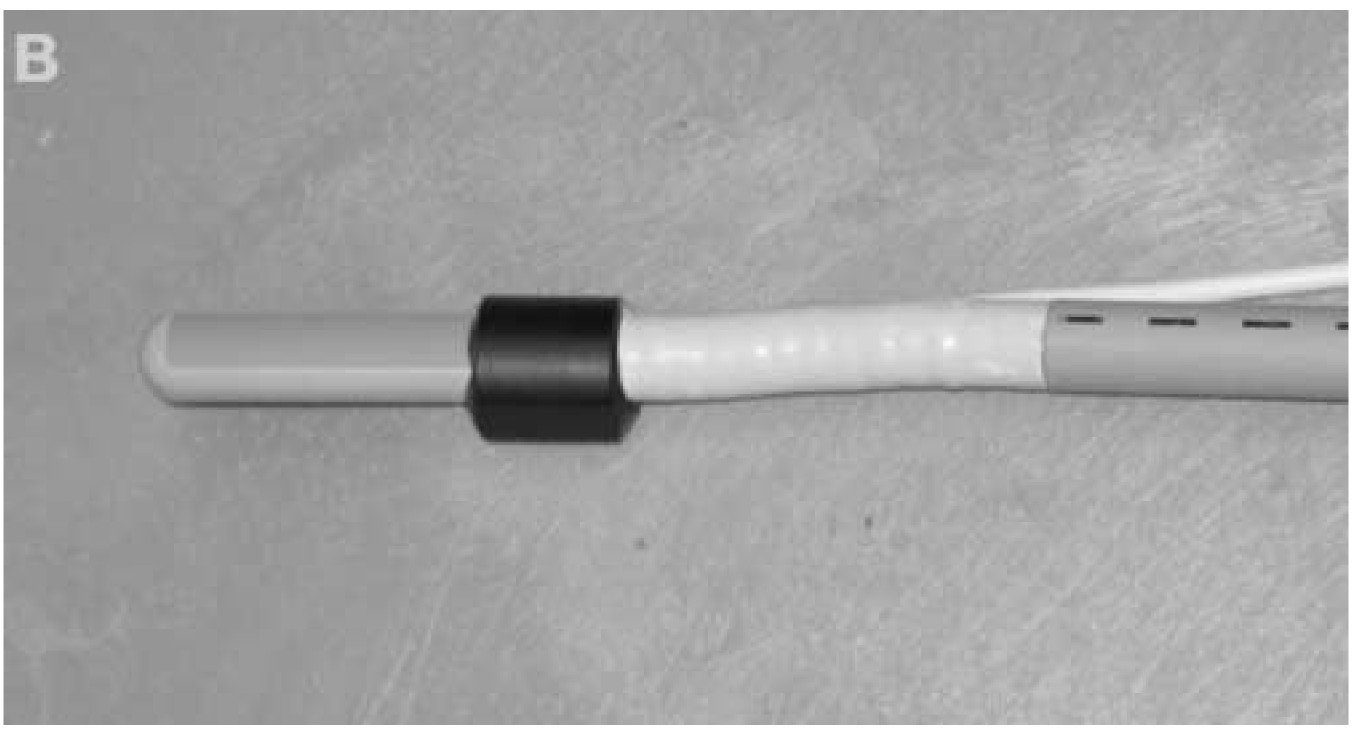


Figure 2A
Click here to download high resolution image

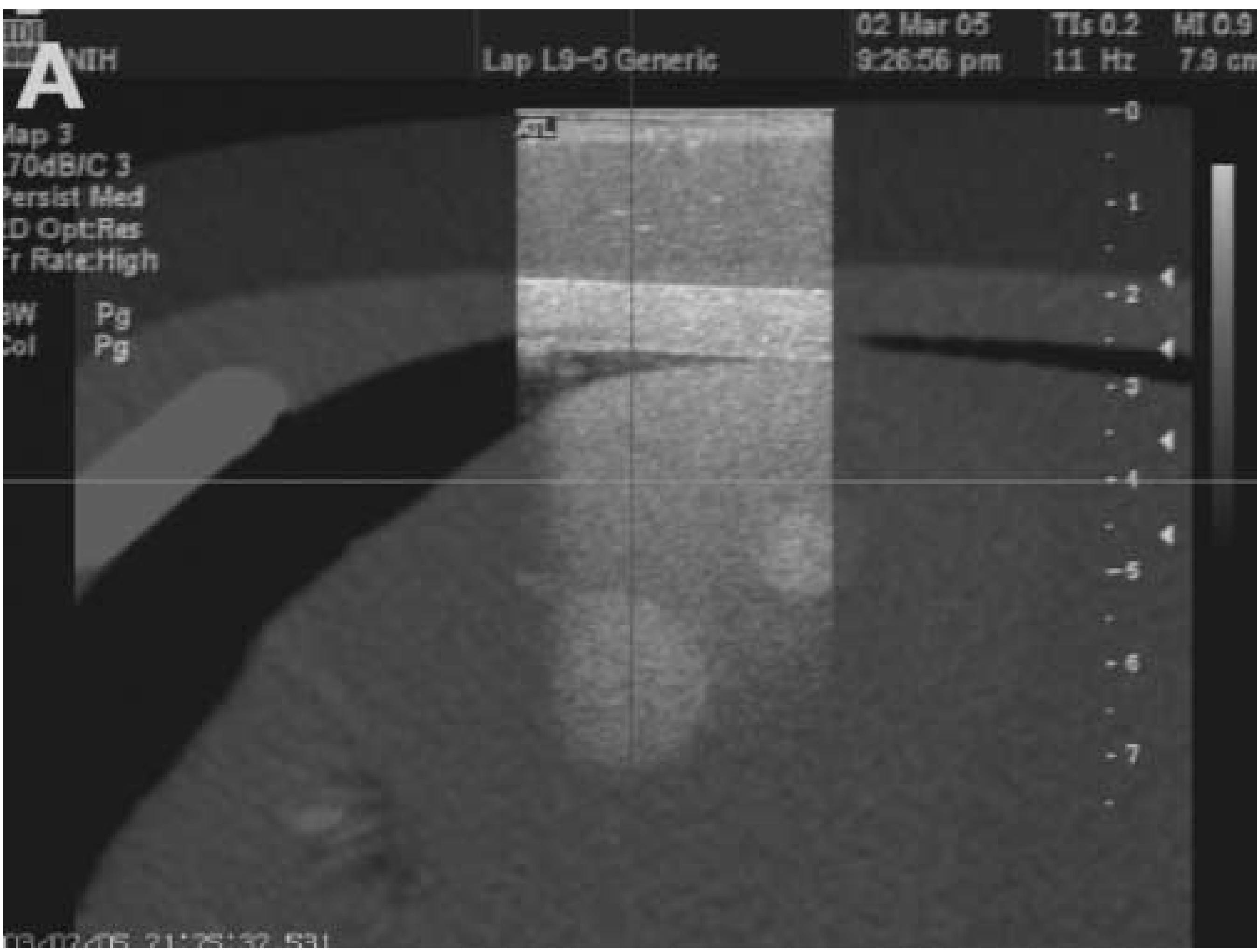


Figure 2B

Click here to download high resolution image

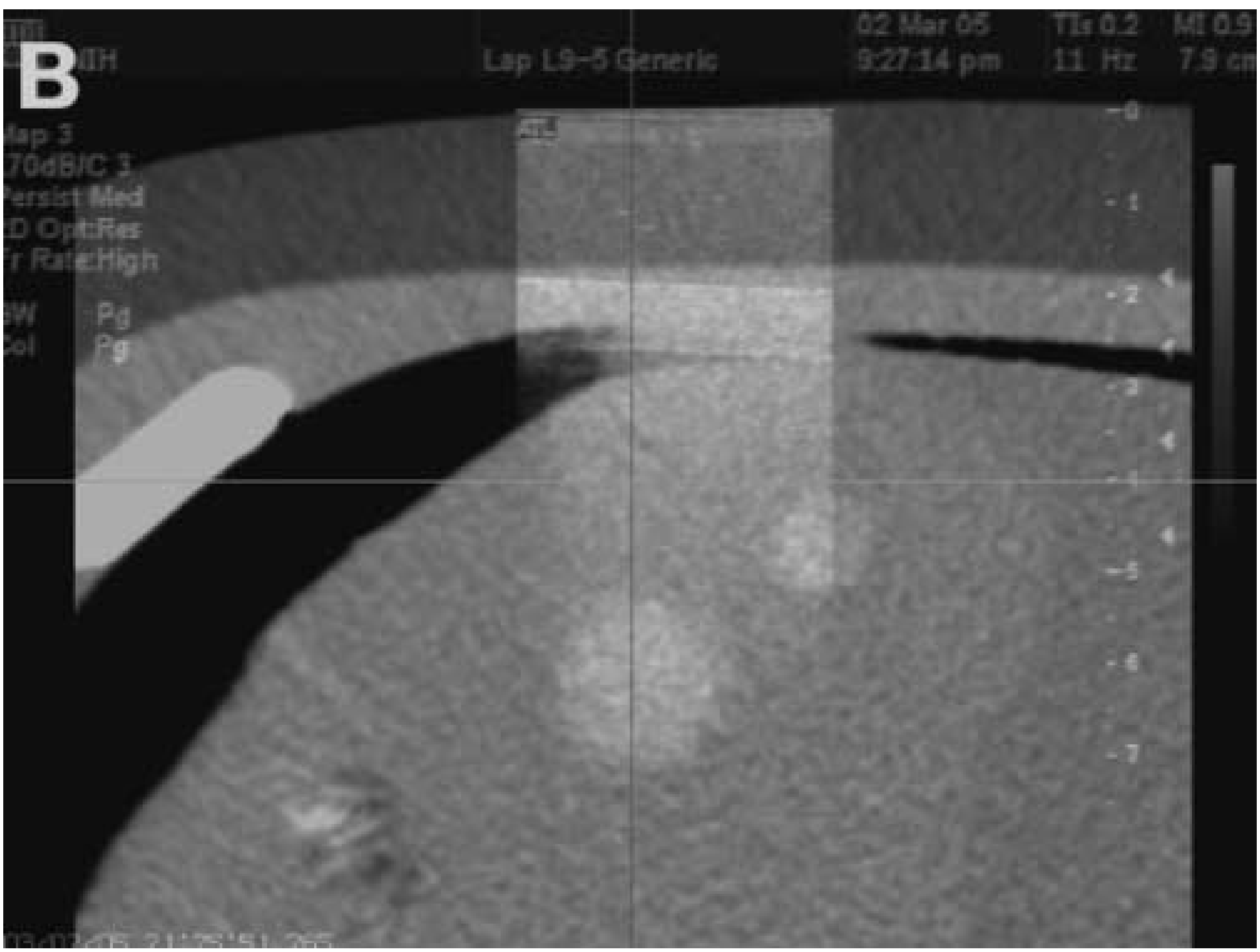


Figure 2C

Click here to download high resolution image

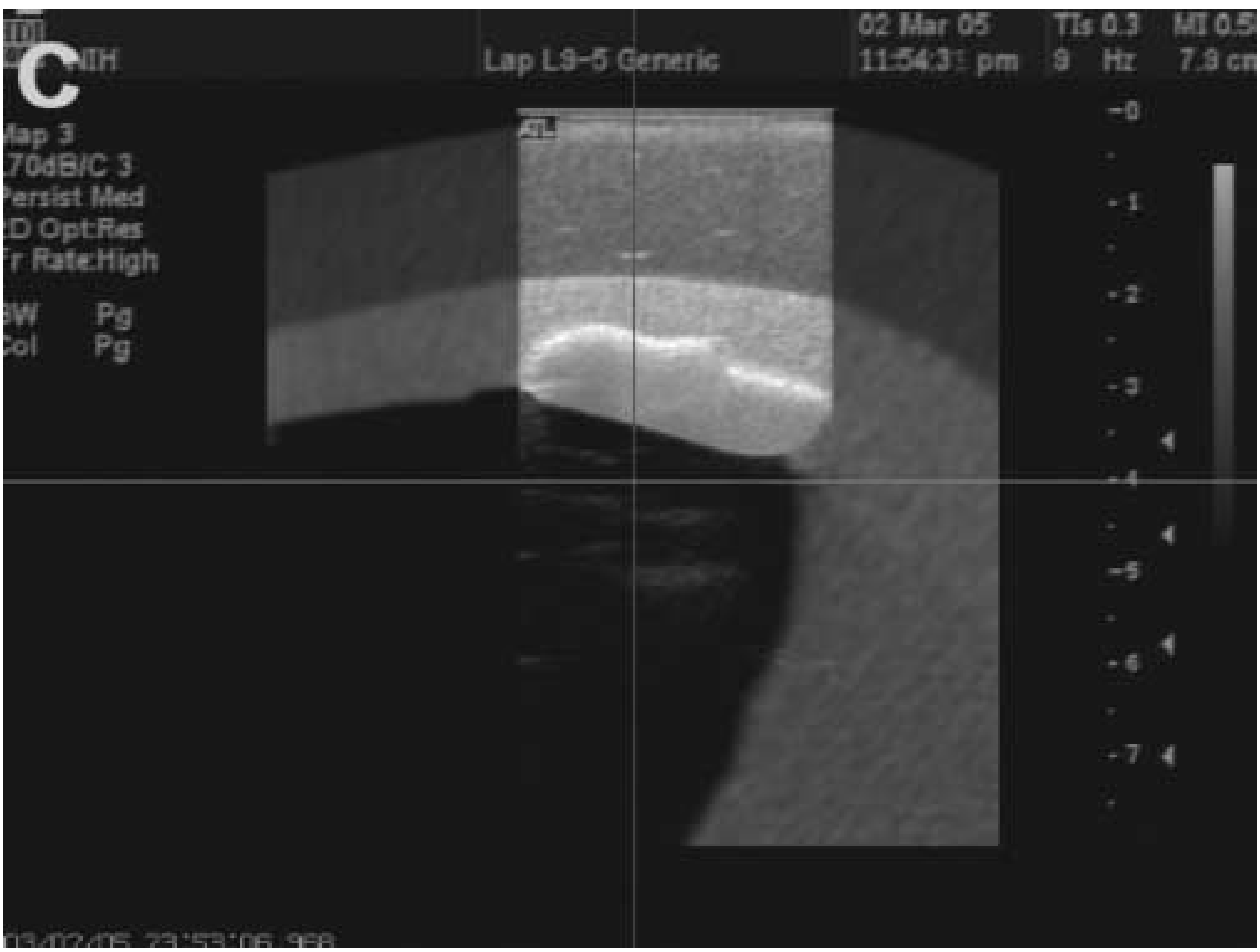
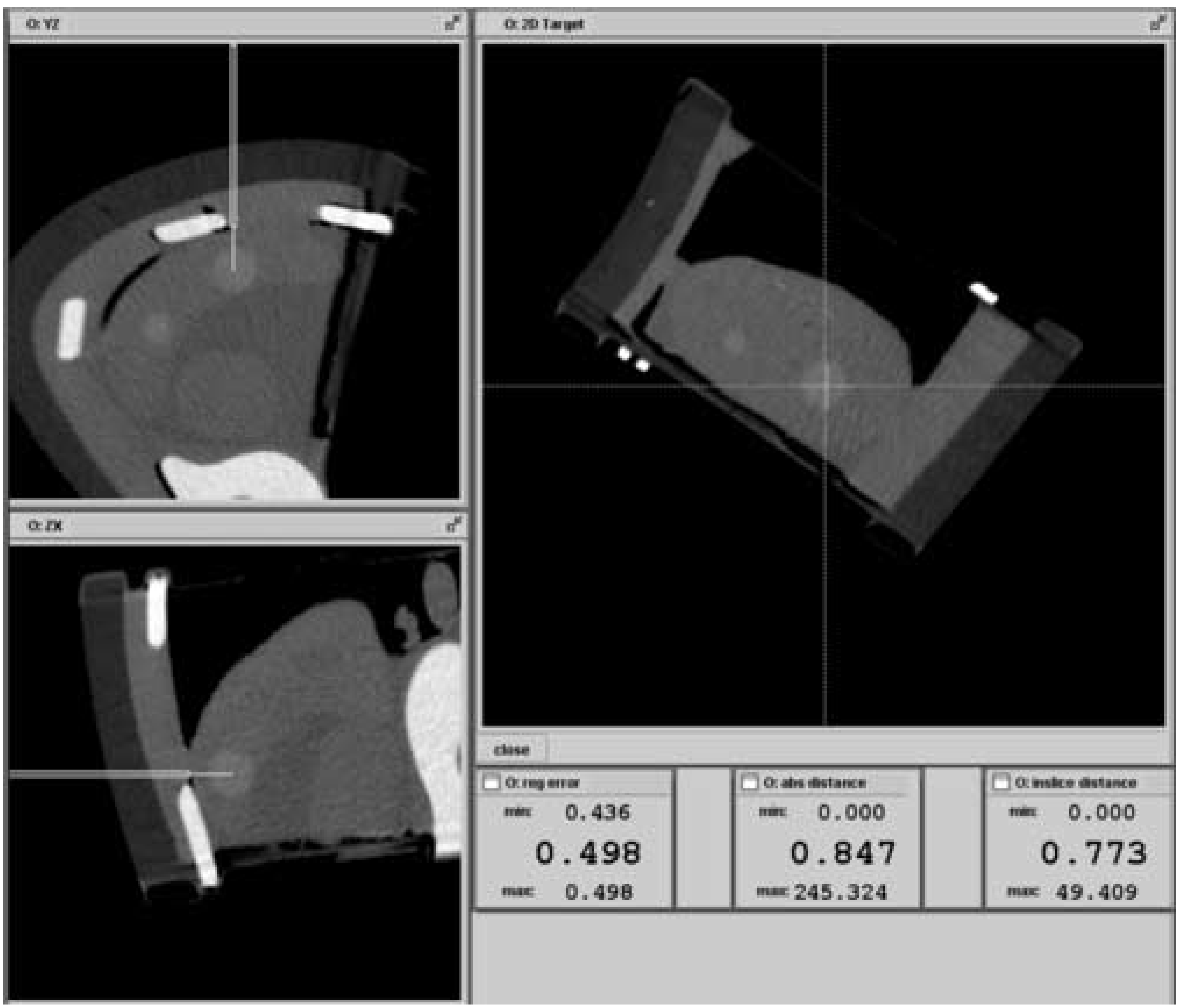


Figure 3
Click here to download high resolution image



Our reference: **ICS 1281** Version Number: 1/2002

ELSEVIER B.V.
TRANSFER OF COPYRIGHT AGREEMENT

Scientific publishers and authors share a common interest in the protection of copyright: authors principally because they want their creative works to be protected from plagiarism and other unlawful uses, publishers because they need to protect their work and investment in the production, marketing and distribution of the article written by the author. In order to do so effectively, publishers request a formal written transfer of copyright from the author(s) for each article published. Publishers and authors are also concerned that the integrity of an article (once refereed and accepted for publication) be maintained, and in order to protect that reference value and validation process, we ask that authors recognize that distribution (including through the Internet/WWW or other on-line means) of the version of the article as accepted for publication is best administered by the Publisher.

To avoid any delay in the publication of your article, please read the terms of this agreement), sign in the space provided and return the complete form to us at the address below as quickly as possible.

Article entitled: **An electro-magnetically tracked laparoscopic ultrasound for multi-modality minimally invasive surgery**

Corresponding author: **Jochen Kruecker, PhD**

To be published in the proceedings: **19th International Congress of CARS – Computer Assisted Radiology and Surgery,Germany, USA, 22-25 June 2005**

I hereby assign to **CARS AND ELSEVIER B.V.**

The copyright in the manuscript named above (the "article") in all forms and media (whether now known or hereafter developed), throughout the world, in all languages, for the full term of copyright and all extensions and renewals thereof, effective when and if the article is accepted for publication. This transfer includes the right to adapt the presentation of the article for use in conjunction with computer systems and programs, including reproduction or publication in machine-readable form and incorporation in retrieval systems.

I understand that a large number of author uses are retained or permitted (without the need to obtain permission from Elsevier) to enable continued use of the article for traditional scholarship communications, for teaching, and for distribution within my institution. I confirm that I have read and understand the full list of rights retained by authors and also agree to the other *General Terms of Publication* (see below).

[ ] I am the sole author of the manuscript
[X] I am one author signing on behalf of all co-authors of the manuscript
[ ] The article is a 'work made for hire' and I am signing as an authorised representative of the employing company
[ ] I am a US Government employee and there is no copyright to transfer, but I affirm the author warranties (see note 4)
[X] I am a co-author who is not a US Government employee but whose co-authors are government employees (see note 4)
[ ] I am an employee of the UK, Canadian or Australian Government claiming Crown Copyright, but I affirm the author warranties (see note 5)
[ ] I am a co-author who is not claiming Crown Copyright but whose co-authors are employees of the UK, Canadian or Australian Government (see note 5)

Please mark **one or more** of the above boxes (as appropriate) and then sign and date the document

Signed: ____________________ Name printed: __**Jochen Kruecker**__________

Title and Company (if employer representative) :____________________

Date: __________**03/11/2005**_____________

Data Protection Act: Please be advised that we hold your details on our database in order to facilitate the publishing of your article and we may occasionally send you the latest news on relevant products from our organisation which has branches world-wide. See also our Web site at http://www.elsevier.com and click on *Privacy Policy*. If you do not wish to be kept up-to-date in this way please mark this box [ ].

A signed fax or copy of this form is sufficient for us to proceed in good faith. However, for legal reasons we still need you to mail us the complete form with the original signature present. Please sign this form in ink and return the complete original, retaining a copy for your files, to:

INTERNATIONAL CONGRESS SERIES
P.O. BOX 993
1000 AZ AMSTERDAM
THE NETHERLANDS
FAX: +31 20 485 3378
EMAIL: ICS@ELSEVIER.COM

General Terms of Publication

1. Rights of authors

The following rights are retained by authors:

- Patent and trademark rights and rights to any process or procedure described in the article.
- The right to include the article in full or in part in a thesis or dissertation provided that this is not to be published commercially.
- The right to photocopy or make electronic copies of the article for their own personal use, including for their own classroom use, or for the personal use of colleagues, provided that the copies are not offered for sale and are not distributed in a systematic way outside of their employing institution (e.g. via an e-mail list).
- The right to retain a pre-print version of the article on an electronic public server.
- The right to post the final published version of the article on a secure network (not accessible to the public) within the author's institution. Posting the final published version of an article on a public file server such as on the World Wide Web can only be done with Elsevier's prior written permission.
- The right, subsequent to publication, to use the article or any part thereof, free of charge in a printed compilation of works of their own, such as collected writings or lecture notes.
- If the article is a 'work for hire' made within the scope of the author's employment, the employer may use all or part of the information in this article for intra-company use.
- The right to present the paper at a meeting or conference and to hand copies of the paper to the delegates attending the meeting.
- The right to prepare derivative works, with full acknowledgement to Elsevier.
- The right to extend the article into book-length form, with full acknowledgement to Elsevier.
- The right to re-use parts of the paper in other works, provided that the new work is not to be published commercially. For commercial publication, prior permission should be sought from Elsevier in writing.

All copies, paper or electronic, or other use of the information must include an indication of the copyright ownership and a full citation of the journal source.

2. Requests from third parties

Requests for all uses not included above, including the authorization of third parties to reproduce or otherwise use all or part of the article (including figures and tables), should be referred to the Elsevier Global Rights Department by going to our Web site at http://www.elsevier.com/homepage/support/ and selecting 'Permissions'.

3. Author warranties

- The article you have submitted to the journal for review is original, has been written by the stated authors and has not been published elsewhere.
- The article is not currently being considered for publication by any other journal and will not be submitted for such review while under review by the journal.
- The article contains no libellous or other unlawful statements and does not contain any materials that violate any personal or proprietary rights of any other person or entity.
- You have obtained written permission from copyright owners for any excerpts from copyrighted works that are included and have credited the sources in your article.
- If the article was prepared jointly with other authors, you have informed the co-author(s) of the terms of this copyright transfer and that you are signing on their behalf as their agent, and represent that you are authorized to do so.

4. US Government employees

- If all co-authors are US Government employees there is no copyright to transfer. Please sign the form, to confirm the author warranties.
- If there is a number of co-authors, of which at least one is a US Government employee (and this work was prepared in such capacity) and at least one is not a government employee, the non-government author should sign this form, indicating transfer of those rights which such author has (also on behalf of any other non-government co-authors).

5. Crown Copyright

- UK Government employee authors may elect to transfer copyright.
- UK Government employees wishing to claim Crown Copyright should mark the appropriate box overleaf and sign the form to affirm the author warranties.
- The work of Canadian or Australian Government employees is automatically subject to Crown Copyright. Please mark the appropriate box and sign the form to affirm the author warranties.
- If there is a number of co-authors, of which at least one is claiming Crown Copyright and at least one is not an employee of the UK, Canadian or Australian Government, the non-government author should sign this form, indicating transfer of those rights which such author has (also on behalf of any other non-government co-authors).

6. Elsevier's AiP (Articles in Press) service

Elsevier may choose to publish an abstract or portions of the paper before we publish it in the journal. Please contact our Production department immediately if you do not want us to make any such prior publication for any reason, including disclosure of a patentable invention.